RADIOCARBON IN THE PACIFIC AND INDIAN OCEANS AND ITS RELATION TO DEEP WATER MOVEMENTS[1]

G. S. Bien, N. W. Rakestraw, and H. E. Suess
University of California, San Diego, La Jolla, California

ABSTRACT

Since 1948, carbon-14 measurements on the bicarbonate of ocean water samples from the Pacific and Indian oceans have been carried out at the Scripps Institution of Oceanography, La Jolla, California. Previous reports of the results of these investigations have been confirmed and amended by many recent measurements. The method of extracting CO_2 from ocean water has been modified and perfected over the past years. The most notable results of the measurements concern the ^{14}C content of deep ocean water which can be interpreted unambiguously by considering the aging of the water during the time of movement from the Weddell Sea eastward and then northward into the North Pacific Ocean.

INTRODUCTION

The principles underlying the method of radiocarbon dating are well known. Natural carbon has an isotopic form, ^{14}C, with a half-life of some 5,730 years. Carbonaceous materials formed subaerially will orginally contain a proportion of ^{14}C practically equal to that in the atmosphere. With time, the radioactive isotope of the fixed carbon will decay and its relative content will indicate the elapsed time since the material was formed from the atmosphere.

Early determinations of the proportion of radiocarbon in the inorganic carbon content of seawater indicated that the results can be accepted only as a relative measure of the "age" of the water, because, in general, surface water cannot be assumed to come into complete equilibrium with the atmosphere before sinking. Therefore, one cannot be certain about the original radiocarbon content in any subsurface sample of seawater. There are also some tenuous assumptions necessary in taking the residence time of the carbon as the residence time of the water itself. Nevertheless, it seems evident that the appropriately defined residence time of the deep water of the oceans is of the order of hundreds of years.

Broecker et al. (1960), in discussing the natural radiocarbon in the Atlantic Ocean, have presented the results of all the prior measurements made in the Atlantic area and have ably discussed the problems involved in their interpretation, including the influence of such factors as the possible introduction of "young" carbon from the oxidation of organic matter and of "old" carbon from the solution of sedimentary carbonate.

The absolute age of the water requires a more or less arbitrary definition; differences in age or residence time, however, are in themselves significant. Differences in radiocarbon content in any large mass of water may be considered from the viewpoint of mixing of the water from different sources or of time spent by the water in going from one place to another. Broecker et al. have been concerned principally with the former alternative in the several water masses of the Atlantic area; we have undertaken to investigate the possibilities of the second alternative in the Pacific and Indian oceans.

As we have already indicated (Bien, Rakestraw, and Suess 1960), the International Geophysical Year afforded us an opportunity to obtain deep samples in a longitudinal section from approximately 40° S lat to 15° N long in the Pacific Ocean. Subsequently, similar samples were obtained in the Indian and the North Pacific oceans, and the results from these have

[1] Contribution from the Scripps Institution of Oceanography, University of California, San Diego.

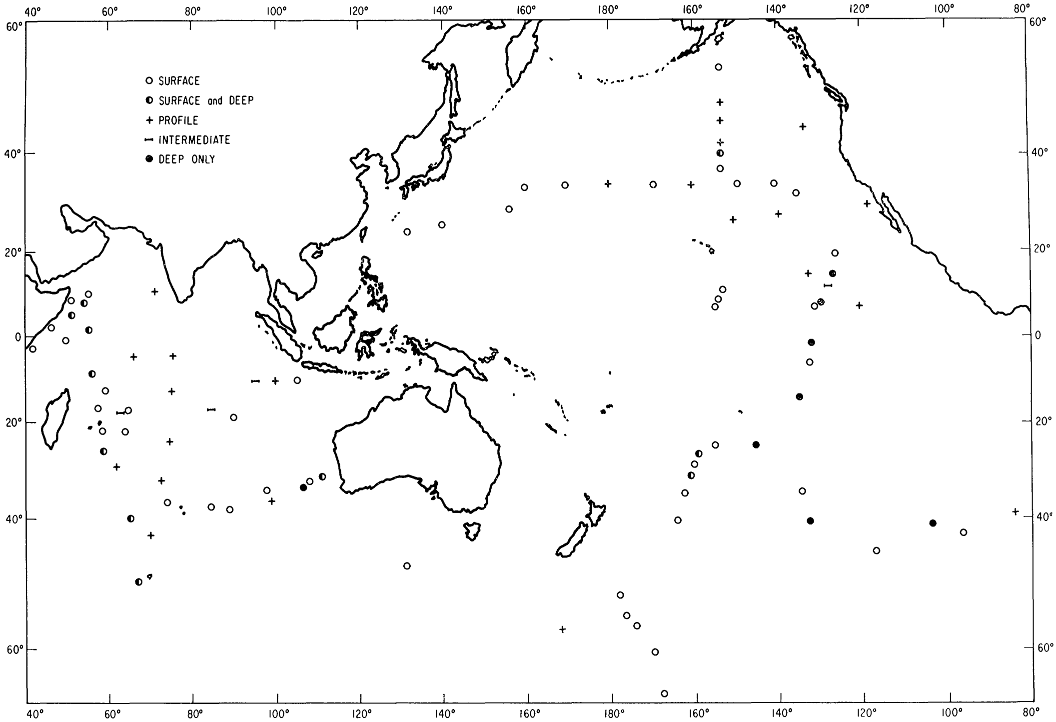

FIG. 1. Location of stations.

been reported elsewhere (Bien et al. 1963*a*, *b*). This paper brings the study up to date with additional results from the Pacific and Indian oceans. Fig. 1 shows the locations from which all samples have been obtained.

METHODS

Water samplers of several designs were constructed, all of an approximate 50-gal (190-liter) capacity. The first of these operated with spring-loaded doors mounted on a central column in the center of the barrel. When cocked, the upper door raised and the bottom lowered, and when tripped off by a falling messenger, both doors snapped shut. These proved reasonably satisfactory, but required frequent attention to adjust the fitting of the doors to prevent leakage when removed from the water.

In a subsequent design, hinged doors opened wide and the barrel went down in the vertical position. When released by a messenger, the barrel turned into the horizontal position and the doors were held firmly shut by a bridle formed by the hoisting cable itself. The weight of the full barrel and the tension of the cable were sufficient to kept the barrel firmly shut even when raised from the water. The loose lines tended to foul, however, and the design was abandoned after the barrel itself was lost in the Indian Ocean.

The final design was a square barrel with spring-loaded doors, the bottom one closing downward inside the barrel. This operated with general satisfaction but was lost in the Indian Ocean before some minor complications were eliminated.

Water samples can be preserved safely for a considerable time in steel drums provided with plastic liners. If closed tightly, exchange of CO_2 with the atmosphere will be insignificant. A few samples were returned in this way, but the usual practice was to treat the samples on shipboard, removing the total CO_2 and precipitating it as insoluble carbonate, in which form it

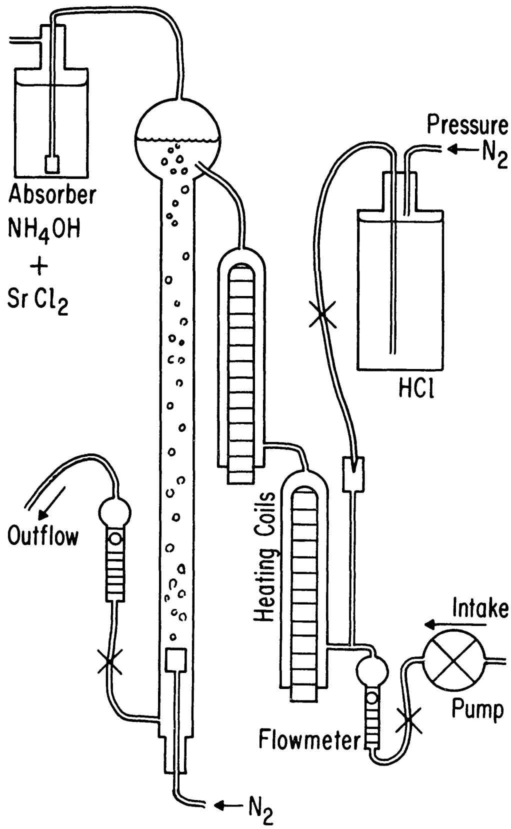

FIG. 2. Processing apparatus. Water enters at the rate of 1.5–2.5 liters/min, is acidified, heated, and the CO_2 stripped by N_2 gas and precipitated as $SrCO_3$.

was returned to the laboratory for further processing and counting.

Originally, the preliminary processing was done in a single batch, the whole sample was acidified in a suitable container, nitrogen gas bubbled through it, and the CO_2 absorbed from the stream in an alkali solution. Complete recovery can require considerable time, however, particularly when cold water must be heated.

In the present method of continuous circulation, the CO_2 can be virtually completely removed from a 50-gal (190-liter) sample in as little as 90 min.

The water is pumped from a plastic drum into the apparatus, and as it enters it is acidified with HCl at a controlled rate. The water passes over electrically heated coils and issues at a temperature of 50 to 70C into the top of a stripping column where it meets a stream of fine bubbles of nitrogen entering the bottom of the column through a sintered-glass diffuser head. The CO_2-free water goes to waste from the bottom of the column while the gas stream passes from the top and enters an absorber bottle through a sintered-glass diffuser. The absorber is a 1-liter Pyrex bottle containing about 800 ml of concentrated NH_4OH made approximately 1 M with $SrCl_2$. Fig. 2 is a diagram of the apparatus. Flowmeters monitor the intake and outflow rates of the water (from 1.5 to 2.5 liter/min), and the rate of addition of HCl is controlled by a needle valve and drop counter.

In our experience, absorption is better in ammonia than in alkali because it can take place in the gas phase as well as in the liquid. The precipitation of $SrCO_3$ is preferable to $BaCO_3$ because barium salts sometimes contain radium, which can cause contamination of the counting gas with radon; strontium salts are usually much less contaminated with radium. The carbonate must be reduced to carbide and hydrolyzed with water to produce C_2H_2, the gas used in our counter.

Our results are expressed as $\Delta^{14}C$; the derivation is as follows:

By definition,

$$\delta^{14}C = \left[\frac{A_{sample}}{A_{std}} - 1\right].$$

Let

$$\delta^{13}C_{sample} = \left[\frac{{}^{13}C/{}^{12}C_{sample}}{{}^{13}C/{}^{12}C_{std}} - 1\right]$$

from mass spectrograph. $\delta^{13}C_W$ = that of 19th century wood, which has an overall average of −0.025. To normalize to 19th century wood, $\Delta^{13}C = \delta^{13}C_W - \delta^{13}C_{sample}$,

$$\Delta^{14}C = \frac{1+\delta^{14}C}{1+2\Delta^{13}C} - 1 = \frac{\delta^{14}C - 2\Delta^{13}C}{1+2\Delta^{13}C}$$

$$= \delta^{14}C - 2\Delta^{13}C(1+\delta^{14}C)$$ (neglecting higher terms). Inserting numerical values, and expressing in per mill,

$$\Delta^{14}C(‰) = \delta^{14}C(‰) - (2\delta^{13}C + 50) \times \left[1 + \frac{\delta^{14}C(‰)}{1{,}000}\right]$$

TABLE 1. *Pacific Ocean*

Sample number	Lat	Long	Depth (m)	Temp. (°C)	Salinity (‰)	$\delta^{13}C$ (‰)	$\Delta^{14}C$ (‰)	Date collected
LJ-410	64°11′ S	168°58′ W	0	1.70	34.009	*	−120 ± 20	13 Feb 1961
LJ-412	60°12′ S	171°32′ W	0	5.50	34.002	*	−66 ± 20	15 Feb 1961
LJ-321	58°20′ S	168°58′ E	0	6.32	34.038	+0.4	−63 ± 6	7 Feb 1961
LJ-320	"	"	740	3.38	34.224	−0.5	−121 ± 8	"
LJ-319	"	"	1,400	2.43	*	−1.3	−155 ± 12	"
LJ-318	"	"	2,100	*	34.766	−2.0	−165 ± 10	"
LJ-317	"	"	2,944	1.48	34.372	−1.1	−167 ± 10	"
LJ-316	"	"	3,825	*	34.277	−1.4	−180 ± 10	"
LJ-414	57°34′ S	144°15′ W	0	*	*	*	−52 ± 7	16 Feb 1961
LJ-413	55°39′ S	177°51′ W	0	*	*	*	−45 ± 4	17 Feb 1961
LJ-417	52°37′ S	178°57′ W	0	*	*	*	−30 ± 5	19 Feb 1961
LJ-418	49°42′ S	178°52′ W	0	9.3	34.34	*	−35 ± 5	20 Feb 1961
LJ- 90	46°30′ S	116° W	0	9.2	34.67	−0.7	−60 ± 8	8 Dec 1957
LJ- 93	42°43′ S	96°06′ W	0	11.5	*	−0.6	−40 ± 8	15 Dec 1957
LJ- 91	42°37′ S	103°20′ W	3,500	1.85	*	−2.5	−180 ± 8	17 Dec 1957
LJ- 69	40°35′ S	132°10′ W	3,500	1.50	34.67	−1.2	−195 ± 8	30 Nov 1957
LJ-408	40°22′ S	164°24′ W	0	*	*	*	−4 ± 20	3 Mar 1961
LJ- 94	39°33′ S	84°10′ W	3,500	1.46	*	−1.9	−196 ± 8	18 Mar 1957
LJ-409	36°27′ S	163°09′ W	0	*	*	*	−7 ± 5	5 Mar 1961
LJ- 68	34°50′ S	135°53′ W	0	17.7	35.05	−0.4	−38 ± 8	15 Nov 1957
LJ-326	34°04′ S	161°54′ W	0	21.4	35.103	*	−24 ± 10	7 Apr 1961
LJ-327	"	"	3,350	*	*	*	−202 ± 10	7 Mar 1961
LJ-415	30°26′ S	160°32′ W	0	*	34.8	*	−12 ± 4	9 Mar 1961
LJ-325	26°29′ S	160°33′ W	0	27.2	35.56	*	−3 ± 20	11 Mar 1961
LJ-324	"	"	3,500	*	*	*	−197 ± 10	"
LJ- 67	25°00′ S	145°00′ W	3,560	1.54	34.65	*	−204 ± 8	23 Nov 1957
LJ-416	24°41′ S	155°15′ W	0	*	34.88	*	−4 ± 4	12 Mar 1961
LJ-877	16°22′ S	161°49′ W	0	*	*	*	19 ± 10	16 Jan 1964
LJ- 57	14°29′ S	135°30′ W	3,450	1.58	34.69	−1.8	−211 ± 8	7 Nov 1957
LJ-876	11°25′ S	117°30′ W	0	*	*	*	46 ± 8	25 Dec 1963
LJ- 66	7°00′ S	132°00′ W	0	26.7	34.68	−1.0	−31 ± 8	26 Feb 1958
LJ- 63	2°08′ S	131°27′ W	3,473	1.52	34.69	−1.3	−214 ± 8	18 Feb 1958
LJ-878	0°	138°58′ W	0	*	*	*	24 ± 8	19 Feb 1964
LJ- 62	5°00′ N	130°00′ W	0	28.0	34.40	−0.1	−33 ± 8	21 Feb 1958
LJ-879	5°00′ N	134°00′ W	0	*	*	*	61 ± 10	21 Feb 1964
LJ-146	5°32′ N	120°05′ W	10	27.5	33.50	−1.22	−75 ± 8	27 July 1959
LJ-140	"	"	485	7.88	34.67	−2.51	−143 ± 8	"
LJ-147	"	"	1,080	4.12	34.63	−1.81	−213 ± 8	"
LJ-494	7°03′ N	158°38′ W	0	*	*	*	−27 ± 5	26 July 1960
LJ- 61	7°08′ N	129°17′ W	2,987	1.48	34.69	−1.4	−228 ± 8	22 Feb 1958
LJ-495	8°14′ N	156°38′ W	0	*	*	*	−9 ± 3	29 July 1960

* No observation.

In translation of $\Delta^{14}C$ results into age, we have used as a starting point the activity of 19th century wood rather than an assumed activity of water at the surface. This is purely arbitrary and does not yield an absolute age for the water. We believe, however, that it facilitates the comparison of different samples.

Accordingly:

Average age of $^{14}C = 8{,}033$ years (using a half-life of 5,568 years).

$$\text{Age} = 8{,}033 \ln \frac{A_{std}}{A_{sample}}$$

$$= 18{,}500 \log \frac{A_{std}}{A_{sample}}.$$

Setting

$A_{std} = 1$,

$A_{sample} = 1 + \Delta^{14}C$, and

$\text{Age} = 18{,}500 \log [1/(1 + \Delta^{14}C)]$.

TABLE 1. Continued

Sample number	Lat	Long	Depth (m)	Temp. (°C)	Salinity (‰)	$\delta^{13}C$ (‰)	$\Delta^{14}C$ (‰)	Date collected
LJ-139	8°29′ N	120°09′ W	2,280	1.97	34.70	−1.66	−253 ± 8	28 July 1959
LJ-137	″	″	3,370	1.58	34.70	−0.74	−211 ± 8	″
LJ-880	10°00′ N	133°00′ W	0	*	*	*	42 ± 10	23 Feb 1964
LJ-493	10°39′ N	155°56′ W	0	*	*	*	−27 ± 4	30 July 1960
LJ- 60	11°00′ N	128°31′ W	400	10.9	34.65	−1.5	−100 ± 8	23 Feb 1958
LJ-467	14°55′ N	133°30′ W	0	*	34.13	*	42 ± 5	20 Jan 1962
LJ-468	″	to	753	6.8	34.51	*	−100 ± 4	″
LJ-470	″	134°14′ W	1,039	4.3	34.56	*	−188 ± 8	″
LJ-476	″	″	1,240	3.72	34.59	*	−161 ± 7	″
LJ-475	″	″	1,711	2.68	34.61	*	−207 ± 9	″
LJ-473	″	″	2,384	1.89	34.56	*	−207 ± 8	″
LJ-471	″	″	2,757	1.73	34.70	*	−227 ± 9	″
LJ-474	14°55′ N	134°14′ W	3,479	1.53	34.67	*	−207 ± 8	20 Jan 1962
LJ- 59	14°58′ N	127°31′ W	2,987	1.66	34.69	−1.2	−222 ± 8	24 Feb 1958
LJ-881	15°00′ N	130°00′ W	0	*	*	*	67 ± 9	24 Feb 1964
LJ-328	15°42′ N	155°22′ W	0	*	*	+1.8	−12 ± 10	21 July 1960
LJ- 58	19°35′ N	125°00′ W	0	24.4	34.69	−0.5	−33 ± 8	26 Feb 1958
LJ-882	20°00′ N	126°40′ W	0	*	*	*	66 ± 9	26 Feb 1964
LJ-561	24°28′ N	131°25′ E	0	25.0	34.87	*	33 ± 9	7 June 1962
LJ-883	25°00′ N	123°00′ W	0	*	*	*	85.7 ± 10	27 Feb 1964
LJ-560	27°11′ N	140°00′ E	0	25.02	35.00	*	64 ± 9	6 June 1962
LJ-1047	27°21′ N	155°00′ W	0	*	*	*	137 ± 10	12 Sept 1964
LJ-420	27°27′ N	150°35′ W	10	25.04	35.283	*	23 ± 5	20 Aug 1961
LJ-420	″	″	716	4.55	34.194	*	−152 ± 7	″
LJ-425	″	″	1,042	3.84	34.436	*	−190 ± 9	″
LJ-426	″	″	2,300	(1.85)	34.665	*	−225 ± 10	″
LJ-427	″	″	3,165	1.55	34.677	*	−223 ± 10	″
LJ-428	″	″	3,630	1.50	34.684	*	−212 ± 10	″
LJ-285	28°12′ N	139°07′ W	538	*	34.061	*	−153 ± 7	15 June 1960
LJ-282	″	″	1,607	*	34.571	*	−233 ± 10	13 June 1960
LJ-283	″	″	2,468	*	34.649	*	−222 ± 11	13 June 1960
LJ-284	″	″	3,518	*	34.680	*	−217 ± 8	14 June 1960
LJ-149	30°04′ N	118°02′ W	10	19.30	33.48	+1.9	−13 ± 8	14 Oct 1959
LJ-150	″	″	75	15.85	33.44	+1.0	−32 ± 8	″
LJ-151	″	″	120	13.40	33.48	+0.2	−38 ± 8	″
LJ-152	″	″	390	6.60	33.16	−1.9	−100 ± 8	″
LJ-153	″	″	600	5.21	34.35	−6.0	−169 ± 8	″
LJ-154	″	″	2,000	2.00	34.66	−1.6	−239 ± 8	″
LJ-158	″	″	3,300	1.60	34.67	+0.3	−235 ± 8	″
LJ-559	30°16′ N	147°49′ E	0	*	*	*	59 ± 10	4 June 1962
LJ-1048	31°29′ N	155°00′ W	0	*	*	*	131 ± 10	10 Sept 1964
LJ-1026	33°48′ N	135°01′ W	0	*	*	*	187 ± 10	7 Aug 1964
LJ-558	34°47′ N	160°20′ E	0	20.4	34.78	*	23 ± 10	2 June 1962
LJ-557	35°00′ N	170°02′ E	0	*	*	*	59 ± 10	31 May 1962

(Continued on next page)

RESULTS

All the results to date have been collected in Tables 1 and 2, with the collection sources arranged from south to north, in both the Pacific and Indian oceans.

Results from deep water below 3,000 m are plotted in Figs. 3 and 4 to show the gradient of variation with latitude.

In the Pacific Ocean the ^{14}C content decreases constantly from south to north well into the northern hemisphere; thereafter the gradient seems to flatten out. This is consistent with Knauss' circulation pattern, later referred to. Extensive mixing probably also takes place.

In the Indian Ocean, the situation is approximately similar but not so clear. ^{14}C decreases from south to north, though not so regularly, with the exception of two stations in the equatorial region. Indeed, at

TABLE 1. Continued

Sample number	Lat	Long	Depth (m)	Temp. (°C)	Salinity (‰)	$\delta^{13}C$ (‰)	$\Delta^{14}C$ (‰)	Date collected
LJ-540	35°00′ N	150°00′ W	0	17.00	34.35	*	−40 ± 10	22 May 1962
LJ-541	35°01′ N	160°00′ W	0	18.06	34.49	*	53 ± 10	24 May 1962
LJ-542	"	"	50	15.27	34.51	*	44 ± 9	"
LJ-543	"	"	100	14.84	34.48	*	16 ± 9	"
LJ-544	"	"	500	7.38	34.00	*	−150 ± 8	"
LJ-545	"	"	1,000	3.46	34.30	*	−150 ± 8	"
LJ-547	"	"	2,000	1.96	34.59	*	−246 ± 10	"
LJ-548	"	"	3,500	1.54	34.68	*	−226 ± 10	"
LJ-546	"	"	4,500	1.49	34.69	*	−320 ± 20	"
LJ-1027	35°00′ N	155°00′ W	0	24.26	34.716	*	140 ± 12	11 Aug 1964
LJ-538	35°02′ N	140°08′ W	0	16.53	34.30	*	74 ± 10	20 May 1962
LJ-550	35°05′ N	180° W	0	17.79	34.80	*	61 ± 10	28 May 1962
LJ-551	"	"	50	17.40	34.76	*	59 ± 10	"
LJ-552	"	"	100	15.48	34.68	*	−22 ± 10	"
LJ-553	"	"	500	7.99	34.06	*	−46 ± 10	"
LJ-554	"	"	1,050	3.58	34.28	*	−184 ± 10	"
LJ-555	"	"	2,000	1.95	34.59	*	−213 ± 10	"
LJ-556	"	"	3,500	1.52	34.66	*	−312 ± 10	"
LJ-549	35°46′ N	170°13′ W	0	17.50	34.69	*	55 ± 10	26 May 1962
LJ-1046	36°49′ N	155°00′ W	0	*	*	*	131 ± 12	7 Sept 1964
LJ-1030	41°00.9′ N	155°00′ W	0	21.8	34.498	*	62 ± 11	13 Sept 1964
LJ-1045	42°09.2′ N	155°02′ W	0	*	*	*	29 ± 10	4 Sept 1964
LJ-429	44°55′ N	134°55′ W	0	16.70	32.756	*	22 ± 5	21 Sept 1961
LJ-430	"	"	1,200	3.0	34.306	*	−189 ± 9	"
LJ-431	"	"	1,700	2.08	34.567	*	−230 ± 9	"
LJ-432	"	"	2,188	1.80	34.615	*	−227 ± 10	"
LJ-435	"	"	2,600	1.65	34.645	*	−202 ± 10	"
LJ-436	"	"	2,996	1.58	34.625	*	−234 ± 10	"
LJ-439	"	"	3,400	*	34.635	*	−227 ± 10	"
LJ-440	"	"	3,630	1.55	34.679	*	−212 ± 10	"
LJ-1033	45°00′ N	155°00′ W	0	15.85	33.031	*	144 ± 12	15 Aug 1964
LJ-1031	"	"	100	7.68	33.382	*	44 ± 11	"
LJ-1032	"	"	200	7.22	33.905	*	−59 ± 8	"
LJ-1040	"	"	500	3.96	34.00	*	−133 ± 8	"
LJ-1039	"	"	998	3.10	34.354	*	−184 ± 8	"
LJ-1038	"	"	4,064	*	*	*	−226 ± 8	"
LJ-1049	47°38.1′ N	155°00′ W	0	*	*	*	80 ± 10	28 Aug 1964
LJ-1037	49°00′ N	154°58′ W	0	11.59	32.654	*	114 ± 10	16 Aug 1964
LJ-1036	"	"	107	4.48	32.865	*	67 ± 8	"
LJ-1034	"	"	210	3.52	33.687	*	−77 ± 11	"
LJ-1035	"	"	498	3.52	34.106	*	−141 ± 8	"
LJ-1041	"	"	1,021	2.81	34.393	*	−199 ± 10	"
LJ-1044	52°56.5′ N	155°03.3′ W	0	*	*	*	101 ± 10	26 Aug 1964
LJ-1042	54°34′ N	155°00′ W	0	11.5	32.721	*	122 ± 12	18 Aug 1964

these stations, at approximately 5° S lat, there is evidence of upwelling. Radiocarbon is unusually low at both stations (*see* Fig. 9) and unusually high in the deep water. As in the Pacific Ocean, the results here are consistent with the assumption of slowly rising deep water in the northern parts of the ocean.

At the northernmost station, the deepest water has an extraordinarily low ^{14}C content, corresponding to an age of some 2,000 years, which seems to be in regular continuation of the ^{14}C gradient from the far south. The layer above it, with a higher ^{14}C activity, seems to be rising, leaving the older water beneath it.

As we have already reported (Bien et al. 1960), the difference in apparent age of the deep water of the Pacific from 40° S lat to 15° N lat is of the order of 300–400 years,

TABLE 2. *Indian Ocean*

Sample number	Lat	Long	Depth (m)	Temp. (°C)	Salinity (‰)	$\delta^{13}C$ (‰)	$\Delta^{14}C$ (‰)	Date collected
LJ-691	51°07′ S	65°51′ E	0	1.63	33.903	*	−56 ± 9	10 Nov 1962
LJ-693	"	"	3,185	0.74	34.71	*	−147 ± 11	"
LJ-489	49°29′ S	132°17′ E	0	9.3	34.339	*	−45 ± 10	12 Jan 1961
LJ-404	42°03′ S	70°45′ E	0	10.88	34.430	*	−36 ± 4	21 Dec 1960
LJ-403	"	"	100	*	*	*	−52 ± 6	"
LJ-401	"	"	1,000	3.35	34.396	*	−120 ± 6	"
LJ-402	"	"	3,000	1.55	34.742	*	−155 ± 7	"
LJ-374	"	"	3,400	1.25	34.689	*	−150 ± 7	"
LJ-689	39°45′ S	64°00′ E	0	14.57	35.372	*	10 ± 12	7 Nov 1962
LJ-690	"	"	4,800	0.7	34.70	*	−123 ± 11	"
LJ-695	37°56′ S	87°38′ E	0	14.2	35.2	*	−26 ± 11	20 Nov 1962
LJ-488	37°51′ S	84°45′ E	0	*	*	*	−22 ± 8	25 Dec 1960
LJ-359	36°18′ S	98°41′ E	0	15.40	35.151	*	−25 ± 10	29 Dec 1960
LJ-383	"	"	100	*	*	*	−35 ± 10	"
LJ-369	"	"	1,066	4.47	34.377	*	−105 ± 9	"
LJ-355	"	"	3,469	1.17	34.718	*	−152 ± 11	"
LJ-698	34°11′ S	105°49′ E	0	16.64	35.737	*	20 ± 10	25 Nov 1962
LJ-699	"	"	3,430	1.50	34.73	*	−162 ± 11	"
LJ-696	33°48′ S	96°01′ E	0	14.90	35.41	*	−36 ± 11	22 Nov 1962
LJ-697	"	"	4,300	*	*	*	−115 ± 12	"
LJ-342	33°21′ S	72°42′ E	0	18.32	35.50	+0.6	−22 ± 9	18 Dec 1960
LJ-339	"	"	1,000	5.44	34.406	−0.04	−95 ± 4	"
LJ-392	"	"	3,050	1.62	*	0.0	−178 ± 8	"
LJ-340	"	"	3,987	1.15	34.703	−0.6	−190 ± 10	"
LJ-486	33°14′ S	108°45′ E	0	18.32	35.50	*	−15 ± 5	1 Jan 1961
LJ-700	32°49′ S	108°39′ E	5,525	*	*	*	−164 ± 10	26 Nov 1962
LJ-686	30°30′ S	61°53′ E	0	18.66	35.584	*	−6 ± 10	4 Nov 1962
LJ-687	"	"	3,400	1.37	34.720	*	−168 ± 10	"
LJ-688	"	"	4,400	0.58	34.688	*	−171 ± 10	"
LJ-684	26°54′ S	58°11′ E	0	21.84	35.56	*	4 ± 12	2 Nov 1962
LJ-685	"	"	5,450	0.93	34.70	*	−164 ± 11	"
LJ-351	23°56′ S	73°53′ E	0	23.86	35.472	*	−16 ± 15	15 Dec 1960
LJ-350	"	"	1,016	4.69	34.418	*	−110 ± 6	"
LJ-349	"	"	1,956	2.54	34.818	*	−172 ± 10	"
LJ-343	"	"	3,339	1.41	34.803	*	−192 ± 10	"
LJ-683	22°00′ S	57°30′ E	0	*	*	*	37 ± 8	31 Oct 1962
LJ-483	18°49′ S	88°33′ E	0	25.53	34.571	*	−7 ± 6	27 Nov 1960
LJ-496	17°19′ S	84°23′ E	350	14.05	35.410	*	−49 ± 5	29 Nov 1960
LJ-682	17°19′ S	57°42′ E	0	*	*	*	35 ± 8	25 Oct 1962
LJ-487	17°15′ S	63°50′ E	0	*	*	*	7 ± 6	5 Dec 1960
LJ-497	16°56′ S	63°50′ E	350	*	*	*	−49 ± 4	5 Dec 1960
LJ-499	14°05′ S	72°15′ E	350	10.30	34.880	*	−63 ± 4	2 Dec 1960

* No observation.
† Complete date unavailable.

(Continued on next page)

corresponding to an overall average velocity of 0.6–0.7 mm/sec based on the simple assumptions that are made. The corresponding velocities in the southern part of the Indian Ocean are of the order of 0.2–0.3 mm/sec. Our subsequent measurements have not changed these conclusions.

DISCUSSION

It was surprising to find the calculated velocities so low. This is connected with the very long residence times, which were also surprising when they were first reported. It would be even more surprising, however, if long residence time were *not* accompanied by slow motion.

There have been efforts to explain the low ^{14}C activity by contamination or mixture with old carbon from some source. This is difficult, because mixing with another water mass requires that the second mass be still older, and this com-

TABLE 2. Continued

Sample number	Lat	Long	Depth (m)	Temp. (°C)	Salinity (‰)	$\delta^{13}C$ (‰)	$\Delta^{14}C$ (‰)	Date collected
LJ-681	13°41′ S	59°42′ E	0	*	*	*	31 ± 8	25 Oct 1962
LJ-484	10°31′ S	105°34′ E	0	28.4	34.41	*	−16 ± 4	19 Oct 1960
LJ-498	10°31′ S	94°55′ E	350	10.27	34.631	*	−111 ± 6	24 Dec 1960
LJ-396	10°28′ S	99°00′ E	100	*	34.336	*	−104 ± 6	12 Nov 1960
LJ-398	"	"	343	10.44	34.675	*	−182 ± 7	"
LJ-395	"	"	960	4.94	34.624	*	−200 ± 7	"
LJ-392	"	"	2,500	2.68	34.672	*	−222 ± 10	"
LJ-394	"	"	3,424	1.33	34.695	*	−212 ± 10	"
LJ-679	9°54′ S	56°20′ E	0	26.32	35.065	*	22 ± 12	27 Oct 1962
LJ-680	"	"	3,480	*	*	*	−167 ± 8	"
LJ-675	5°54′ S	63°47′ E	0	27.94	34.518	*	−55 ± 14	14 Oct 1962
LJ-676	"	"	1,000	5.85	34.78	*	−180 ± 10	"
LJ-677	"	"	2,943	1.76	34.74	*	−176 ± 10	"
LJ-678	"	"	3,920	1.60	34.72	*	167 ± 10	"
LJ-1063	5°52′ S	55°00′ E	0	25.42	35.226	*	49 ± 7	Oct 1962†
LJ-1066	"	"	100	*	*	*	−16 ± 8	" †
LJ-1067	"	"	200	*	*	*	−54 ± 7	" †
LJ-1065	"	"	300	*	*	*	−68 ± 8	" †
LJ-1064	"	"	500	*	*	*	−122 ± 10	" †
LJ-670	5°21′ S	75°06′ E	0	27.94	34.518	*	−52 ± 14	10 Oct 1962
LJ-672	"	"	1,000	5.78	34.78	*	−143 ± 10	"
LJ-673	"	"	2,970	1.78	34.74	*	−154 ± 10	"
LJ-674	"	"	5,000	1.38	34.72	*	−129 ± 10	"
LJ-1052	1°16′ S	41°30′ E	0	24.62	35.207	*	−1 ± 7	4 Aug 1964
LJ-1053	1°58′ S	49°20′ E	0	25.74	35.246	*	23 ± 6	9 Aug 1964
LJ-1054	2°00′ N	45°38′ E	0	24.30	35.016	*	−5 ± 10	12 Aug 1964
LJ-1061	2°07′ N	55°04′ E	0	27.02	35.321	*	49 ± 7	30 Aug 1964
LJ-1062	"	"	>2,000	*	*	*	−191 ± 7	"
LJ-1055	5°00′ N	50°51′ E	0	25.07	35.462	*	−5 ± 10	15 Aug 1964
LJ-1056	"	"	2,000	*	*	*	−212 ± 8	"
LJ-661	8°16′ N	70°37′ E	0	28.46	36.36	*	−28 ± 14	6 Oct 1962
LJ-662	"	"	100	20.45	35.51	*	−68 ± 11	"
LJ-663	"	"	200	13.37	35.20	*	−13 ± 13	"
LJ-664	"	"	400	10.85	35.17	*	−121 ± 11	"
LJ-665	"	"	600	9.54	35.12	*	−125 ± 12	"
LJ-666	"	"	800	8.38	35.08	*	−128 ± 11	"
LJ-667	"	"	1,000	7.18	35.05	*	−143 ± 12	"
LJ-668	"	"	1,995	2.73	34.80	*	−184 ± 12	"
LJ-669	"	"	3,200	1.71	34.73	*	−192 ± 12	"
LJ-670	"	"	3,800	1.66	34.73	*	−244 ± 14	"
LJ-1058	8°53′ N	53°09′ E	<2,000	*	*	*	−145 ± 7	20 Aug 1964
LJ-1057	9°18′ N	51°03′ E	0	13.32	35.113	*	−93 ± 7	18 Aug 1964
LJ-1059	10°14′ N	53°01′ E	0	25.89	35.837	*	24 ± 10	27 Aug 1964
LJ-1060	"	"	>2,000	*	*	*	−190 ± 7	"

pounds the problem. Solution of sedimentary carbonate has also been suggested as a source of carbon of low activity, but the carbonate in the upper surface of the sedimentary layer, available for solution, contains young carbon supplied continuously from above. It would require unusual erosional processes to bring into solution very much of the old carbon deeper in the sediment. Broecker et al. (1960) have also discussed this source and dismissed it as unimportant.

Mixing of water, contamination with other sources of carbon, oxidation of organic matter, or solution of fresh carbonate—all would result in increasing the ^{14}C content and decreasing the residence time or age.

The calculated velocities are an order of magnitude less than any previously sup-

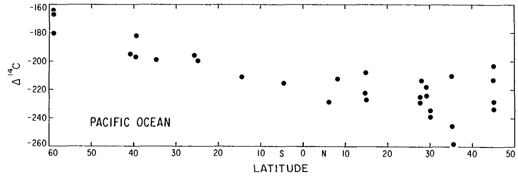

FIG. 3. Carbon-14 in the Pacific Ocean below 3,000 m, vs. latitude.

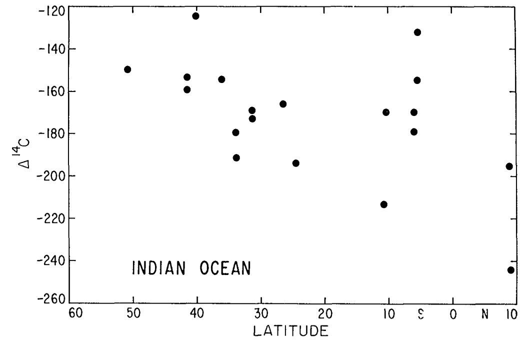

FIG. 4. Carbon-14 in the Indian Ocean below 3,000 m, vs. latitude.

posed for deep water movements. Calculations must always be checked with direct current measurements, and few direct measurements of deep water movements have been attempted. Neutrally-buoyant floats have given useful results in many cases, but in very deep water they have not always been satisfactory. Some unpublished results have been reported to us of such measurements in the Indian Ocean at 2,000 m. A casual inspection of these indicates that while the speed may be 2 cm/sec or more, the resultant velocity vectors at nearby stations may vary in direction by as much as nearly 180°.

We believe that the movement of the deep water is in a large sense random, and that one cannot measure the time it takes for the water to travel long distances in terms of small-scale velocities. For this purpose, we believe that the differences in residence times, which we have measured by radiocarbon dating, are more suitable, even if only approximate.

In the general theory of deep water movement, it is recognized that there are only two sources of deep water—in the very northern Atlantic Ocean (probably including the Norwegian Sea) and in the Weddell Sea in Antarctica. These two water masses not only fill the deep Atlantic basins but also contribute, in unknown proportion, to the eastward drift around the south of Africa into the Indian Ocean and on into the Pacific Ocean. The only source of deep water in the Indian and Pacific oceans, therefore, is in the south.

It is generally supposed that in each

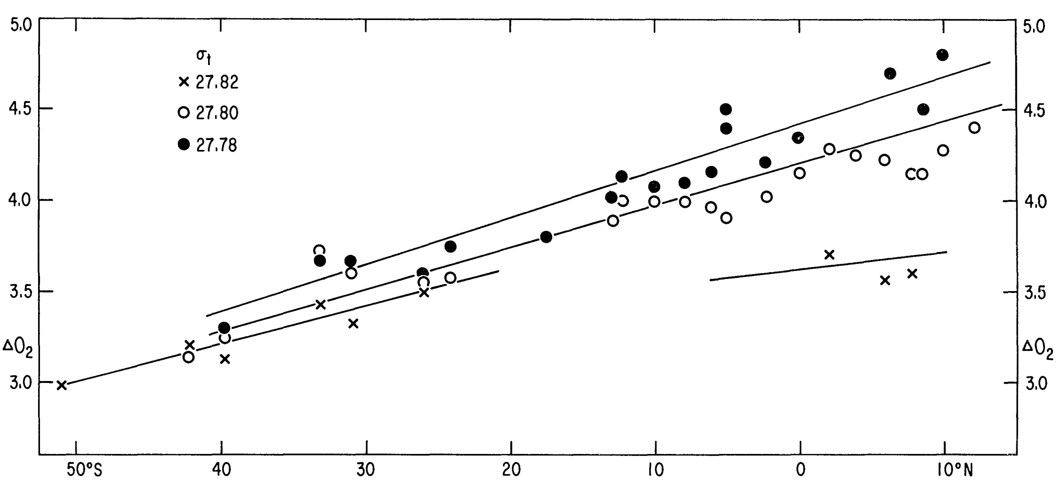

FIG. 5. Oxygen consumption vs. latitude in the deep water of the Indian Ocean. Saturation concentrations of oxygen minus observed values, at different sigma-*t* surfaces, 27.78, 27.80, and 27.82 (bottom).

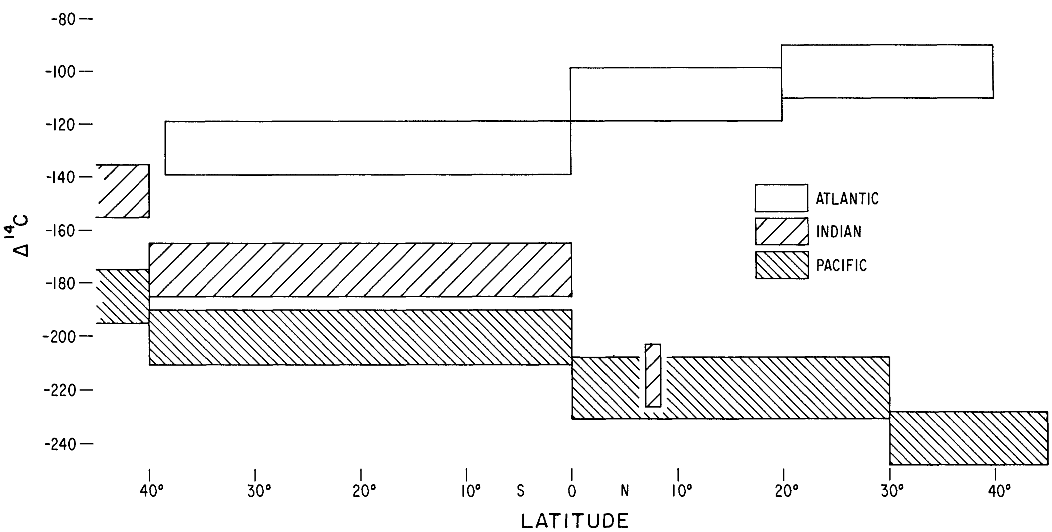

FIG. 6. Average ^{14}C content below 3,000 m in zonal areas in the Pacific, Indian and Atlantic oceans. Width of the bars indicates the average error of determination. Values for the Atlantic quoted from Broecker et al.

ocean, the strongest deep movement is along the western boundary, and Stommel's theory involves return movements along the eastern boundary as well as a slow general diffusion upward through the thermocline.

The circulation in the deep Pacific Ocean has been discussed by Wooster and Volkmann (1960) and by Knauss (1962), who has made use of our earlier results on ^{14}C age. On the basis of the temperature distribution, he suggests a general movement of deep water northward, a little stronger in the western basin, a slow upwelling in the very North Pacific, and a probable widespread return in the upper layers. He is concerned, however, with the difficulty of explaining the transport figures according to the generally accepted model of the circumpolar current. In the latter connection, we would point out that one can calculate a zonal velocity along the edge of the circumpolar current at least, by using the ^{14}C figures at three of our stations: 1), 51°07′ S lat, 65°51′ E long; 2), 58°20′ S lat, 168°58′ E long; and 3), 39°33′ S lat, 84°10′ W long. The last of these is rather too far north, but using the figures for the deep water, one can calculate an overall velocity of 1.4 mm/sec. If this is approximately true, it indicates that the deep circumpolar current moves much more slowly than heretofore supposed.

It should be observed that the ^{14}C measurements confirm the picture of northward movement of deep water in both oceans, without any indication of a return southward in the eastern part of the ocean, as has been suggested. Knauss' theory of slow rise in the north, and Stommel's model of general upward diffusion through the thermocline are both consistent with our results.

The calculation of overall velocities from the differences in radiocarbon age assumes, of course, that the direction of motion is in the direction of decreasing ^{14}C content. This is from south to north, and there is no question of this being the direction in which the deep water moves in the Pacific Ocean. Knauss has clearly shown this from the distribution of temperature. A similar analysis of the Indian Ocean has not yet been made, but there seems to be little doubt of its similarity.

The gradient of oxygen consumption has also been used to indicate the direction of water movement, and Fig. 5 shows the calculated values of oxygen consumption

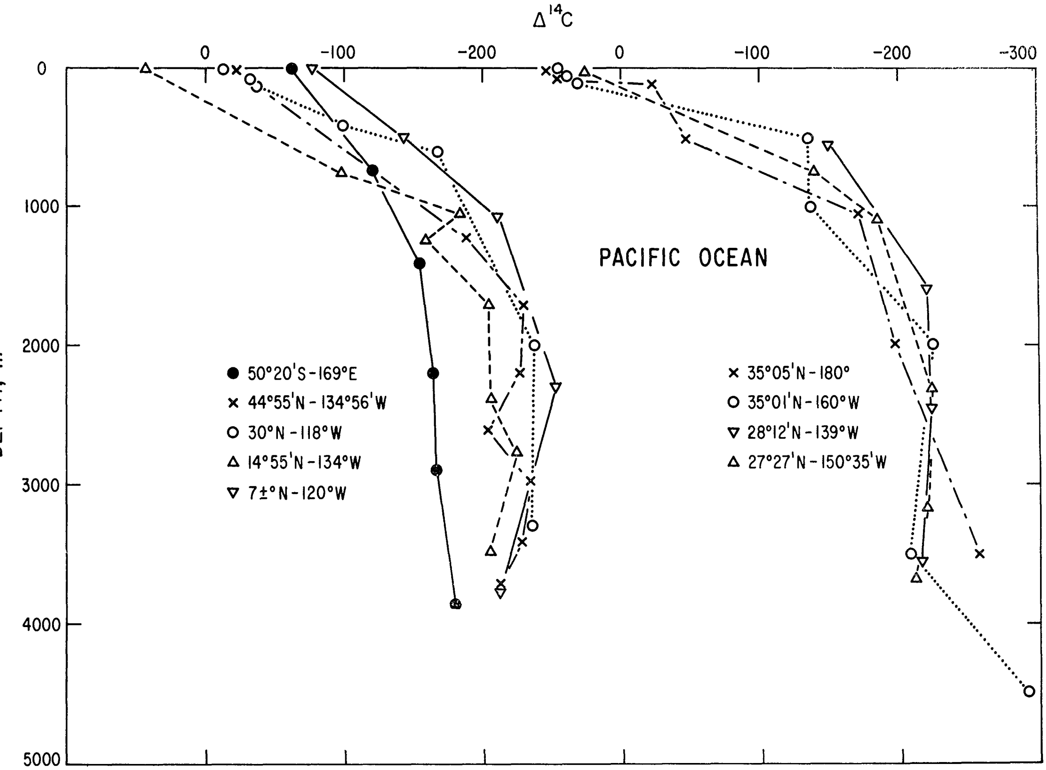

FIG. 7. Vertical profiles of $\Delta^{14}C$ at stations in the Pacific Ocean.

at a number of stations in the Indian Ocean plotted against latitude. Increase of oxygen consumption is a clear indication of northerly movement.

To treat our results in accordance with the general model of deep water circulation, the Pacific and Indian oceans were divided into zonal areas: below 40° S lat; from 40° S lat to the equator; from the equator to 30° N lat; and beyond 30° N lat (in the Pacific Ocean only). All the values for ^{14}C in each of these areas below 3,000 m were averaged and the results are shown in Fig. 6 In similar fashion, the Atlantic Ocean was divided into zonal areas and the deep water values given by Broecker et al. were averaged. ^{14}C activity in the deep water decreases from south to north in both the Pacific and Indian oceans and from north to south in the Atlantic Ocean, approaching a common value where the circulation model postulates continuity between the South Atlantic and the Indian oceans.

VERTICAL DISTRIBUTION

Figs. 7 and 8 extend the data that we reported previously on the vertical distribution of ^{14}C. At any one station, radiocarbon is relatively constant with depth below 2,000 m within a range of ±10%. There are a few notable exceptions, particularly at two stations where activity is abnormally low at the lowest depth. This seems to suggest a source of "dead" carbon from the bottom. We have already dismissed the possibility of solution of sedimentary carbonate, but it is conceivable that local volcanic activity might be responsible. However, we believe that a more likely explanation is the one already given. Both these stations are in the northern parts of the Pacific and Indian oceans, respectively, where slowly rising deep water could leave the deepest and oldest water behind.

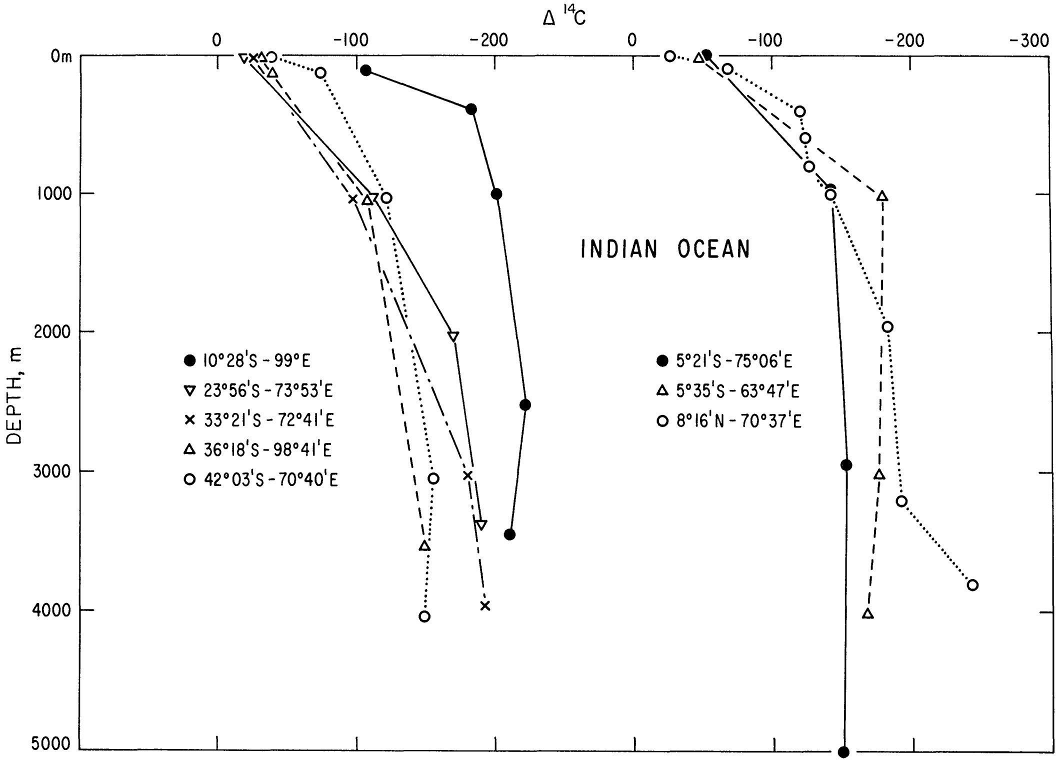

FIG. 8. Vertical profiles of $\Delta^{14}C$ at stations in the Indian Ocean.

The concentration gradients in the upper parts of these profiles may be important in interpreting mixing phenomena and the exchange with the atmosphere.

RADIOCARBON IN THE SURFACE

Fig. 9 shows values for ^{14}C in surface water in the Pacific and Indian oceans, plotted against latitude for different years from 1958 to 1964. Two points are significant: the decrease in ^{14}C from north to south, with extremely low values in the far south; and the general increase of ^{14}C at all latitudes from 1958 to 1964. The overall increase is, of course, the result of artificial nuclear activity, with greater effect in the northern hemisphere. The very low ^{14}C values in the high southern latitudes remain relatively unaffected. As reported before, these doubtless result from upwelling of deep water and its failure to come into equilibrium with the atmosphere. Future observations, extended over several more years, will eventually make it possible to deduce quantitative data for the rates of exchange and mixing that determine the observed ^{14}C concentrations on the surface of the oceans.

ACKNOWLEDGMENT

We gratefully acknowledge help, at various stages of the project, from Warren S. Wooster, John A. Knauss, and Joseph L. Reid, Jr. Ship operations and the collection of samples were completed with the support of Atomic Energy Commission Contract AT (11-1)-34, Project No. 74. Radiocarbon measurements were financed through a National Science Foundation Grant.

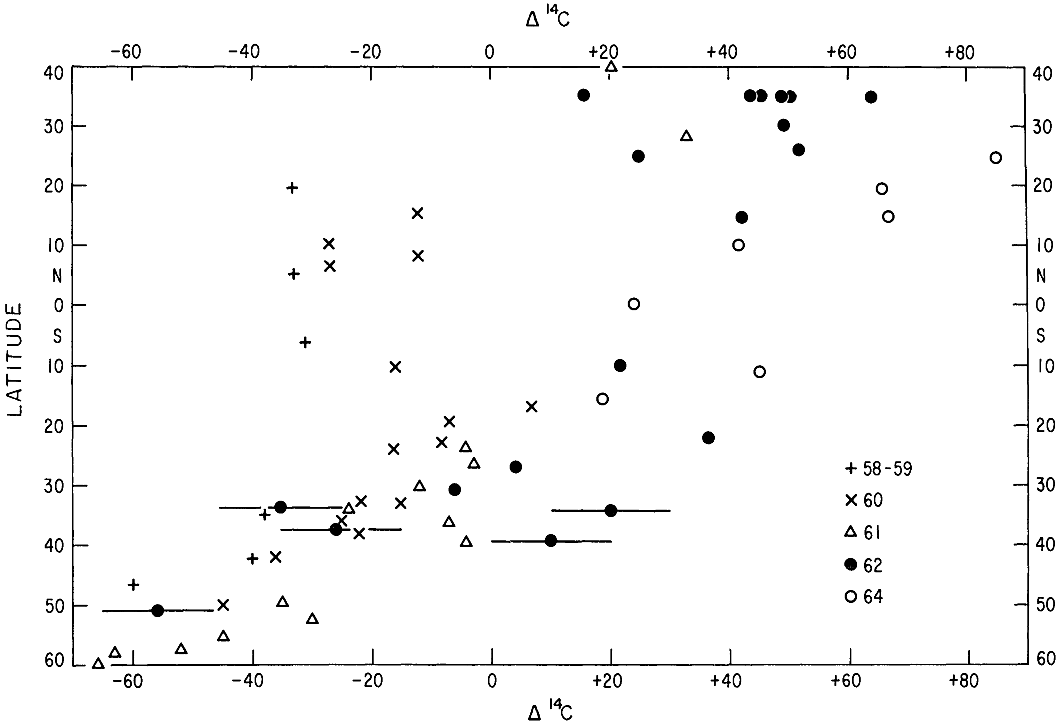

FIG. 9. Carbon-14 in the surface of the Pacific and Indian oceans, vs. latitude and in years from 1958 to 1964.

REFERENCES

BIEN, G. S., N. W. RAKESTRAW, AND H. E. SUESS. 1960. Radiocarbon concentration in Pacific Ocean water. Tellus, **12:** 436–443.

———, ———, AND ———. 1963*a*. Radiocarbon dating of deep water of the Pacific and Indian Oceans. Bull. Inst. Oceanog., **61:** 12–16. *Also in* Radioactive dating, p. 159–173. Intern. Atomic Energy Agency, Vienna.

———, ———, AND ———. 1963*b*. Natural radiocarbon in the Pacific and Indian Oceans. Nuclear Sci. Ser. Rept. No. 38, p. 152–160. Publ. 1075, NAS–NRC, Washington, D.C.

BROECKER, W. S., R. GERARD, M. EWING, AND B. C. HEEZEN. 1960. Natural radiocarbon in the Atlantic Ocean. J. Geophys. Res., **65:** 2903–2931.

KNAUSS, J. A. 1962. On some aspects of the deep circulation of the Pacific. J. Geophys. Res., **67:** 3942–3954.

WOOSTER, W. S., AND G. H. VOLKMANN. 1960. Indications of deep Pacific circulation from the distribution of properties at five kilometers. J. Geophys. Res., **65:** 1239–1249.